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A PRELIMINARY REPORT ON THE NASA SHEET ALLOY SCREENING PROGRAM FOR MACH 3 TRANSPORT SKINS*

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The general approach taken by NASA in formulating a program for screening sheet alloys to be used in the skins of a Mach 3 commercial transport airplane is presented, and some preliminary results of this program are given.

A general review of the performance requirements, possible configurations, and operating problems of such an airplane has been presented by Stack and his associates (1).[3] In addition, the 1961 International Air Transport Assn. (IATA) Symposium on Supersonic Air Transport (2) treats these problems further and gives detailed studies of the economic and human factors.

In order to be economically feasible a minimum life of 30,000 hr is required, with reliability at least equal to present-day subsonic transports. Cruise will be at altitudes between 65,000 and 70,000 ft, with skin temperatures between 500 and 600 F. Economic and operating considerations dictate that the airplane should have reasonable subsonic efficiency as well as high supersonic efficiency. During deceleration from supersonic cruise altitude to subsonic approach and hold altitude the skin temperature may drop to well below zero, depending on the atmospheric conditions. Cabin pressure differentials will be significantly higher than in present-day aircraft and will be dictated in large part by considerations for the safety and comfort of the passengers. Cabin depressurization at cruise altitude could be serious and tolerable depressurization rates would be considerably less than for present-day transports because of the longer times necessary for descent to a safe altitude. Therefore maintaining complete structural integrity of the fuselage becomes extremely important, and present-day requirements for fail-safe design may have to be modified.

It is quite obvious that the development of a Mach 3 transport offers a tremendous challenge to the materials engineer and presents problems not entirely shared by any military aircraft. As pointed out during the IATA Conference (2), the problem of proper material selection appears to be the most difficult and the least understood. Present-day aluminum alloys cannot be used in most of the structure, and stainless steels, titanium, or superalloys are required. A judgment concerning the feasibility of developing a commercial aircraft from these metals requires knowledge of mechanical properties not now available and application of the most advanced testing techniques.

It is considered that the major portion of the materials problem lies in selecting

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[3] The boldface numbers in parentheses refer to the list of references appended to this paper.

alloys for wing and fuselage skins. In 1961 this problem was reviewed in some detail in a paper by Brown et al (3) which contains an extensive bibliography. On the basis of this review it was concluded that particular attention should first be given to two major material characteristics: (1) unstable crack propagation resistance (fracture toughness), and (2) stability of mechanical properties under long-time load at moderately elevated temperatures. Material classes of interest appeared to be the precipitation hardening stainless steels, titanium alloys, and superalloys. An extremely meager amount of data was available to select materials from these classes on the basis of the above-mentioned material characteristics. In fact, the conventional tensile properties in many cases were not accurately established in the temperature range of interest, therefore a large number of candidate alloys had to be considered. The mechanical properties of most of these alloys are conventionally varied by cold working or heat treatment or both. The number of alloys and conditions having potential interest exceeded 50.

Quite obviously a screening program was needed to reduce this number of candidate alloys and conditions to permit intensive study of a reasonable number of materials. Because of the magnitude of the program it was necessary to divide the effort among several laboratories. Cooperating organizations are the University of Michigan and the University of Syracuse.[4] This paper describes the general approach to the screening program and gives results obtained using this approach. Most of the data shown have been obtained in the authors' laboratory; however, in a few cases these results have been supplemented by selected data from progress reports issued by the cooperating organizations (**4,5**).

It is hoped that this preliminary report will encourage alloy producers to adopt similar means when evaluating their new materials for this application and that those engaged in materials research will be encouraged to direct their attention to the interesting but complex problems of the commercial trisonic transport.

APPROACH TO THE SCREENING PROGRAM

The program was so planned that it could be completed in 12 to 18 months with the funds available. It is obvious that any screening program of this magnitude and nature is a compromise regarding both the number and the range of the variables included. Ideally, the program should permit rapid sorting of the alloys on the basis of the two major material characteristics previously mentioned, through the use of techniques yielding reproducible results by different investigators. A screening procedure previously employed by the authors in more limited programs (**6,7**) was to make the testing conditions so severe that there was reasonable assurance of eliminating all potentially undesirable alloy conditions. Unfortunately this approach is not possible in the present case. Thus 30,000-hr tests are not practical and cycling of load or temperature or both becomes prohibitively expensive and time-consuming. The following discussion will briefly outline the nature and possible consequences of the compromises made.

Material Conditions:

The various alloy conditions under investigation are given in Appendix I,[5] along with the names of the principal

[4] The Materials Research Laboratory, Richton Park, Ill., is also cooperating by conducting solid salt corrosion screening tests at elevated temperatures. This work, under the direction of E. J. Ripling, is not discussed herein.

[5] See p. 855.

investigators. The sheet thickness was chosen as 0.025 in. This selection was arbitrary and it should be remembered that toughness may be a function of thickness. The cold reductions and heat treatments employed were designed to yield a wide range of strength levels. For since a large body of sharp-notch data on sheet alloys shows many high-strength materials are very directional, particularly if cold worked.

Selection of Test Specimens:

Tests were confined to static tension

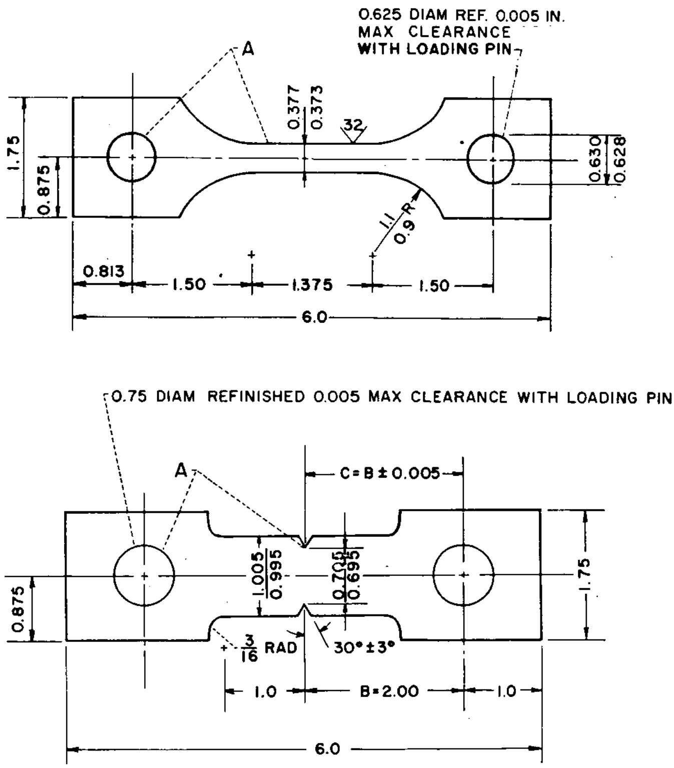

FIG. 1.—Sharp-Edge-Notch and Smooth Tension Specimens.

A surfaces true to centerline within 0.001 in.; notch root radius 0.0007 in. maximum; unless otherwise noted, dimensions may vary ±0.01 in.

the superalloys it was in some cases necessary to develop optimum aging treatments from systematic tests at room temperature.

All material conditions were tested in both the longitudinal (rolling) direction and in the transverse (perpendicular to rolling) direction. This investigation of directionality effectively doubles the number of tests but is quite necessary using the sharply notched and smooth specimens shown in Fig. 1. The smooth ultimate tensile and yield strengths are useful in assessing the strength potential of an alloy and are of direct value to the aircraft designer. These tests also provide the elastic modulus which is of particular interest for lightweight structures which are stiffness controlled.

The 1-in. wide sharp-edge-notch specimen recommended by the ASTM Special Committee on Fracture Testing of High-Strength Materials (8,9) was used to give a qualitative indication of the fracture toughness (resistance to unstable crack propagation). This specimen has proved quite valuable in evaluation of high-strength sheet alloys for solid propellant and cryogenic fueled rocket tanks. Its use in the present program also permitted direct comparison of the results with a substantial body of room-temperature sharp-notch data already obtained on certain alloys of interest to the supersonic transport. It was recognized that this test would possibly lack useful sensitivity at yield strength to density values below about 550,000. This is not of great consequence in evaluating rocket tank alloys because the desired strength to density values are above 700,000. However, the supersonic transport may employ alloys with yield strength to density values somewhat below 500,000. Therefore the possibility exists that follow-on investigations of fracture toughness using larger specimens may eliminate a few alloys passed in the present screening program.

Test Conditions:

The operating temperature range of interest extends from perhaps −50 to 600 F. The screening program test temperatures extend from −110 to 650 F. All alloy conditions were tested in this temperature range, with the majority of tests being performed at the extremes and at room temperature. Testing at −110 F ensures that the presence of a transition temperature near the lowest anticipated service temperature will be uncovered. The upper test temperature was extended to 650 F in order to indicate whether the operating temperature was close to that causing rapid loss of strength. Smooth and sharp-notch data in the temperature range between −110 and 650 F serve as a baseline for evaluating stability effects.

In order to estimate the comparative stability of the smooth and sharp-notch tensile properties, specimens were subjected to *exposure* at 650 F for 1000 hr under a relatively low stress and then tested over the temperature range between −110 and 650 F. The exposure temperature was selected as 650 F rather than the average skin temperature of 550 F with the thought that raising the temperature would in part compensate for the relatively short exposure time employed. Mechanical property changes with time and temperature are generally the result of diffusion-controlled processes such as overaging or precipitations occurring during the exposure. If overaging were the only process taking place, the substitution of a higher temperature for a longer time should be satisfactory since the strength decreases continuously with either time or temperature. However, if exposure also produces precipitation the situation is more complicated. Thus it is known (10,11) that the notch properties may be adversely affected by precipitations occurring during creep tests and that this deterioration is more pronounced if the precipitations occur at low temperatures over long times than if they occur in relatively short times at higher temperatures. Therefore, the relatively short-time high-temperature exposure used in the screening program may not always reveal fracture toughness deterioration which could occur during a 30,000-hr service period. Again follow-on tests must be depended upon to define stability more accurately.

The selection of the exposure stress was arbitrary and roughly approximates that corresponding to a 1-*g* load on the airplane. A value of 40,000 psi was used for the steels and superalloys. For

TABLE I.—COMPOSITION OF ALLOYS INVESTIGATED.[a]

Alloy	Condition	Heat Number	Element, per cent													
			Carbon	Manganese	Silicon	Phosphorus	Sulfur	Chromium	Cobalt	Nickel	Molyb-denum	Aluminum	Vanadium	Iron	Titanium	Other
AM350	20, 30, and 45 per cent cold rolled 12 in. wide strip	W23327-1 CEVM Allegheny Ludlum Steel Corp.	0.084	0.65	0.21	0.009	0.007	16.50	...	4.29	2.94	...	...	balance	...	0.10 N_2
Inconel W	50 and 65 per cent cold rolled 12 in. wide strip	3565-WL International Nickel Co., Inc., Huntington Division	0.04	0.50	0.59	...	0.007	15.19	...	74.19	...	0.68	...	6.23	2.52	
V-36	20, 30, and 50 per cold rolled 12 in. wide strip	22021-2 CEVM Allegheny Ludlum Steel Corp.	0.291	0.91	0.20	0.008	0.013	24.85	40.36	20.26	3.92	...	...	2.47	...	1.60 columbium 2.12 tungsten
Ti-8Al-1Mo-1V	mill anneal at 1450 F for 18 hr	V-1551 Titanium Metals Corp. of America	0.032	...	...	...	...	...	...	...	1.1	7.8	1.1	0.09	balance	0.0055 H_2 0.013 N_2

[a] Ti-8Al-1Mo-1V 0.020 in. thick, all others 0.025 in. thick.

titanium alloys the stress was reduced to 25,000 psi because of the lower density of these materials. Under these stresses most alloys should not experience plastic flow except possibly at the root of the very sharp notch. It is recognized that the designer must consider loads due to gusts and maneuvers specimens were fully machined before exposure. For notched specimens good arguments can be made for machining either before or after the exposure. In the present investigation it was desired to simulate the influence of exposure on material in an airplane structure containing a crack. A cracked skin would be

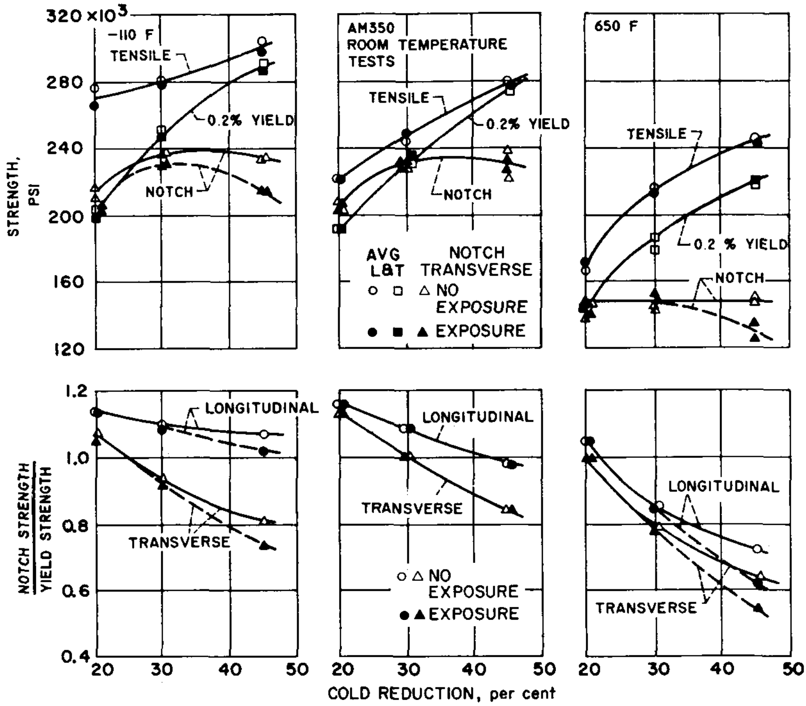

FIG. 2.—Influence of Cold Reduction on Smooth and Sharp-Notch Properties at Three Temperatures for AM 350 (825 F, 3-hr Temper) Tested Before and After a 1000-hr Exposure at 650 F and 40,000 psi.

which can give rise to considerably higher stresses. However, accurate assessment of these loads requires knowledge of not only the configuration to be employed but also the operating environment and flight characteristics of the airplane. The study of varying stress effects appears best suited to a follow-on program which also incorporates realistic load and temperature cycling.

Both the sharp-notch and smooth subjected to long-time exposure at the operating temperature under relatively low stress conditions existing at cruise.

TEST RESULTS

The data presented in this section are from the authors' laboratory for the alloys AM 350, Inconel W, V-36, and Ti-8Al-1Mo-1V. The compositions of these alloys, along with other pertinent details, are given in Table I. Testing techniques are described in Appendix II.[6] Generally, at each test temperature, one smooth and duplicate notch tests were made in the longitudinal and transverse directions for both exposed and unexposed specimens. Data for longitudinal and transverse specimens or

Elastic moduli are not presented in this report but are available to those who may need this information. The elongation is not reported since it is of primary concern in fabrication and does not relate to the alloy properties under study.

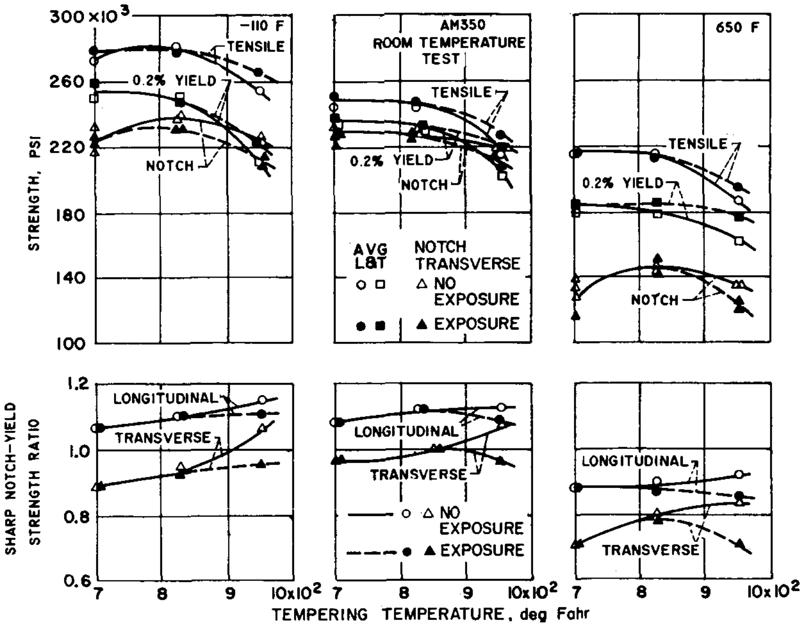

Fig. 3.—Influence of Tempering Temperature on Smooth and Sharp-Notch Properties at Three Temperatures for AM 350 (30 per cent Cold Rolled) Tested Before and After a 1000-hr Exposure at 650 F and 40,000 psi.

for exposed and unexposed specimens have been averaged where there was no measurable effect of these variables. However, an exception has been made in the case of AM 350 where individual transverse notch-test data points are shown in order to illustrate typical scatter. Where significant notch sensitivity is encountered, use is made of the ratio between the sharp-notch strength and 0.2 per cent tensile yield strength to illustrate qualitatively the variation in fracture toughness with material condition or test temperature.

Alloy AM 350:

The results for this alloy (Figs. 2 to 4) are interesting in that they clearly illustrate the influence of cold reduction, heat treatment, and test temperature on the smooth strength and sharp-notch characteristics of an alloy which is unstable during the exposure.

In order to simplify the representations only the transverse notch-strength values are plotted. However, the longitudinal sharp-notch - yield strength ratio is shown. The effects of exposure will be considered separately since they do not fundamentally alter the dependence of

[6] See p. 856.

the strength properties on cold reduction, heat treatment, or test temperature.

Influence of Cold Reduction.—The influence of cold reduction is illustrated in Fig. 2 for sheet tempered 3 hr at 825 F. As might be expected, both the smooth tensile and yield strength at all test temperatures increase continuously with cold reduction. However, the effects of cold reduction are reflected differently in the tensile strength than in the yield strength because of austenite transformation during the tension test. If the alloy has received heavy cold reductions nearly all the austenite will be transformed during rolling. However, moderate reductions leave a considerable amount of austenite untransformed, and under these circumstances transformation will take place during the tension test. The amount of martensite formed during the tension test will then be a function of the test temperature, low temperatures producing the most transformation. These mechanisms explain the relatively low yield-tensile ratios observed at −110 F for sheet rolled 20 per cent and the increase in the yield-tensile ratio with increasing cold reduction observed for tests at −110 F and room temperature. For tests at 650 F less martensite is formed by the tensile strain than at the lower test temperatures. As a result the yield-tensile ratio

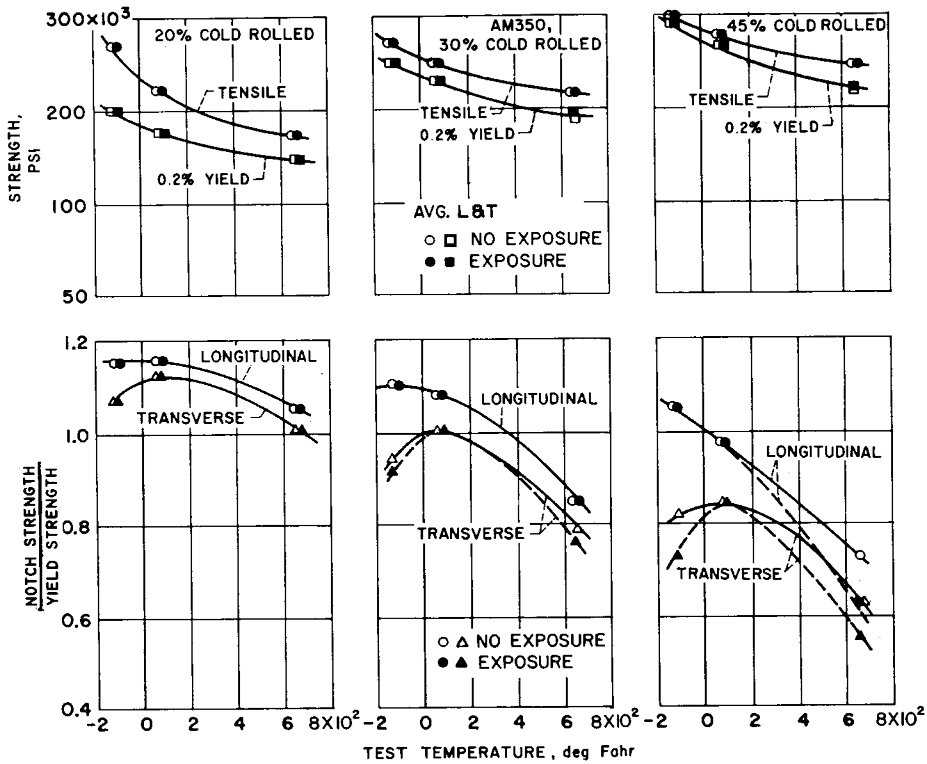

FIG. 4.—Influence of Test Temperature on the Smooth and Sharp-Notch Properties for Three Cold Reductions of AM 350 (825 F, 3-hr Temper) Tested Before and After a 1000-hr Exposure at 650 F and 40,000 psi.

at 650 F is nearly independent of cold reduction.

The sharp-notch yield strength ratio exhibits a continuous decrease with increasing cold reduction at all three test temperatures. It will be noted that the transverse direction possesses distinctly lower toughness than the longitudinal direction.

Influence of Tempering Temperature on AM 350.—The influence of tempering temperature is illustrated in Fig. 3 for sheet rolled 30 per cent. Both the smooth tensile and yield strengths at all three test temperatures remain nearly constant between tempering temperatures of 700 and 825 F and then decrease with increasing temperature. As might be expected, the yield to tensile strength ratio changes very little with variation in the tempering temperature.

It would be expected that the sharp-notch - yield strength ratio would increase with increasing tempering temperature and this behavior is followed. Again it is noted that sheet tested in the transverse direction exhibits lower toughness, but differences between the two testing directions decrease as the tempering temperature approaches 950 F.

Influence of Test Temperature on AM 350.—The influence of test temperature is shown directly on Fig. 4 for sheet rolled 20, 30, and 45 per cent and tempered 3 hr at 825 F. The smooth properties follow the expected trend of decreasing strength with increasing test temperature. It will be noted that the temperature-dependence of these properties is most pronounced below room temperature. Only small changes in strength occur in the temperature range between 500 and 650 F. Therefore the strength values obtained at 650 F are closely representative of those corresponding to cruise conditions.

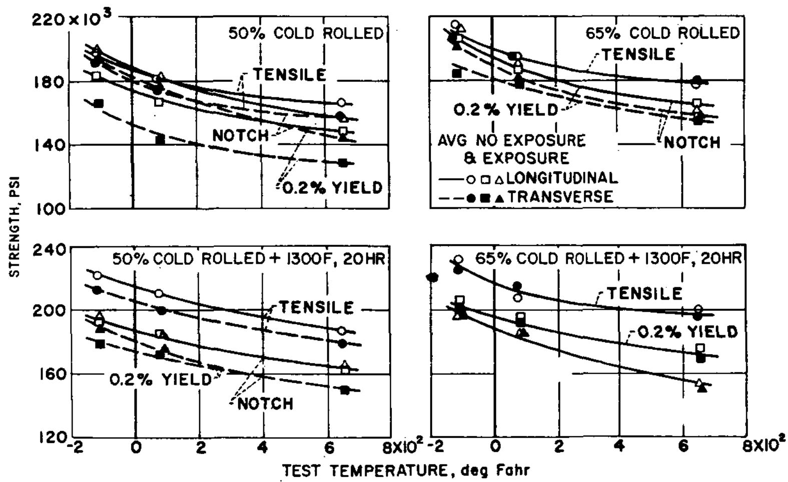

FIG. 5.—Influence of Test Temperature on the Smooth and Sharp-Notch Properties for Several Conditions of Inconel W Tested Before and After a 1000-hr Exposure at 650 F and 40,000 psi.

The sharp-notch - yield strength ratio depends on the test temperature in a rather complex manner. From the trend of the yield strength, the ratio might be expected to increase with increasing test temperature. An increase in the ratio between −110 F and room temperature is, in fact, observed for transverse tests.

However, for all conditions the sharp-notch-yield strength ratio is *lower* at 650 F than at room temperature. This difference is more pronounced as the cold reduction increases, and sheet rolled 45 per cent and tested at 650 F has rather low sharp-notch-yield strength ratios in both testing directions. It is also interesting to note that the cold rolled transverse notch tests. As might be expected it is most pronounced at those testing temperatures (−110 and 650 F) producing the lowest toughness (see Fig. 4). The exposure embrittlement appears to increase with both the cold reduction and the tempering temperature (see Figs. 2 and 3). Sheet rolled 20 per cent and tempered at 825 F showed

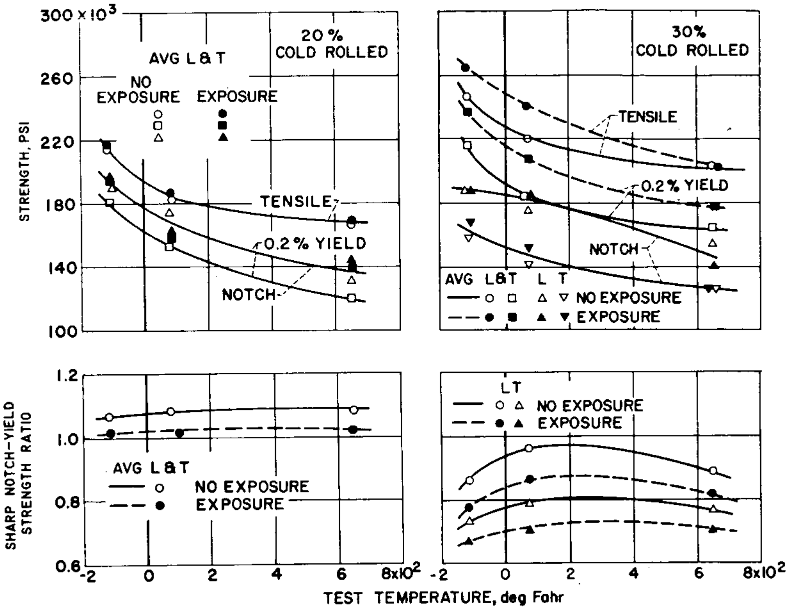

FIG. 6.—Influence of Test Temperature on Smooth and Sharp-Notch Properties for Several Conditions of V-36 Alloy Tested Before and After a 1000-hr Exposure at 650 F and 40,000 psi.

conditions investigated were apparently less tough at 650 F than at −110 F.

Influence of Exposure on AM 350.—The data on exposed specimens (see Figs. 2 to 4) reveal embrittlement resulting from a 1000-hr 650-F exposure at a stress (40,000 psi) insufficient to produce plastic flow in the smooth specimens. The general effect of the exposure is to lower the notch strength and for the most exposure-sensitive conditions also to raise the yield strength.

The embrittlement caused by exposure is revealed by both longitudinal and no exposure effects on the present series of tests. However, it is possible that longer exposure times or tests on larger notch specimens would reveal some embrittlement.

Inconel W Alloy:

The data for Inconel W cold rolled 50 and 65 per cent with and without a subsequent age are shown in Fig. 5 as a function of test temperature. Both the smooth tensile and yield strengths decrease with increasing test temperature but show only a mild temperature-dependence between 500 and 650 F. There is a definite directionality in the smooth tensile and yield strengths of 50 per cent cold rolled sheet, with the transverse direction being weaker. At 65 per cent cold reduction only the yield strength exhibits this directionality, and to a lesser extent. As might be expected, aging after cold reduction increases the strength properties and reduces the directionality.

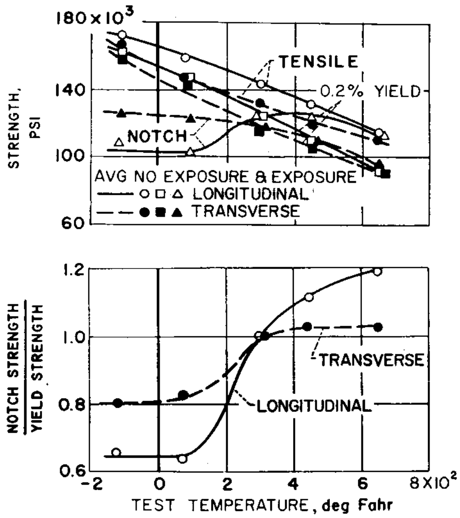

FIG. 7.—Influence of Test Temperature on Smooth and Sharp-Notch Properties for Ti-8Al-1Mo-1V Tested Before and After a 1000-hr Exposure at 650 F and 25,000 psi.

The sharp-notch strength is essentially equal to or above the yield strength except for sheet cold rolled 65 per cent and aged. For this latter condition the toughness appears to decrease somewhat with increasing test temperature. Within the limits of scatter the notch - yield strength ratio exhibits no significant directionality, and no effect of exposure could be defined for either the notch or smooth properties.

Alloy V-36:

The data for V-36 cold rolled 20 and 30 per cent are shown in Fig. 6. The smooth tensile and yield strengths exhibit no directionality and as might be expected, change only a small amount in the temperature range between 500 and 650 F.

The sharp-notch - yield strength ratio for 20 per cent cold reduced sheet exhibits no directionality, is above unity, and is nearly independent of test temperature. For 30 per cent cold reduction the notch-strength ratio is influenced by both testing direction and test temperature, with the transverse direction having the lower toughness. The influence of testing temperature is such that the notch strength ratio at −110 and 650 F is lower than at room temperature.

The effects of the exposure are rather complex and reflected only in raising the smooth strength values. For both cold reductions the yield strength at all test temperatures is elevated about 10 per cent by exposure. On the other hand, the tensile strength is unaffected by exposure for sheet rolled 20 per cent but raised at the lower test temperatures for material rolled 30 per cent. The reduction in sharp-notch - yield strength ratio due to exposure is, of course, a reflection of the elevation in yield strength.

8Al-1Mo-1V Titanium Alloy:

Data for this alpha titanium alloy are given in Fig. 7 as a function of test temperature. In contrast to the previously discussed alloys, the smooth strength values show a relatively strong temperature-dependence in the temperature range between 500 and 650 F. A directionality in smooth properties is observed at intermediate test temperatures, with the longitudinal smooth strength values being higher than the transverse. At −110 F and 650 F the directionality is much smaller.

The sharp-notch - yield strength ratio

exhibits a pronounced directionality such that the longitudinal direction is less tough at the lower test temperatures but apparently more tough at 650 F. It should be noted that both directions have a transition temperature above room temperature.

No effects of the exposure were observed on either the smooth or notch strength values.

CRITERIA FOR COMPARISON OF ALLOYS

In comparing alloys on the basis of their sharp-notch properties use is generally made of the ratio between the notch strength and the tensile strength or between the notch strength and the yield strength. These ratios may then be plotted as a function of either the tensile strength to density or yield strength to density values. When alloys are tested under identical conditions these plots are useful in estimating the relative order of fracture toughness at a particular strength level.

Aircraft designers frequently use the tensile strength as a baseline metal property and the notch strength to tensile strength ratio as an indication of the relative toughness. This procedure is perfectly satisfactory for a large number of alloys used in present-day aircraft construction because the tensile strength is sensitive to those factors influencing the notch strength. Therefore the sharp-notch tensile strength ratio for a given alloy is a continuous function of its tensile strength. However, for the alloys reported here the yield strength is sometimes more sensitive to exposure than the tensile strength (for example, 20 per cent cold rolled V-36, Fig. 6). Furthermore, use of the sharp-notch - tensile strength ratio may be misleading when the alloy is unstable during the tension test. Thus, the −110-F sharp-notch - *tensile* strength ratio of AM 350 cold rolled 20 per cent (see Fig. 2) is rather low and is less than that for 30 per cent cold reduction. However, it is only reasonable to expect that both these alloy conditions are quite tough and that the toughness decreases, not increases, with cold reduction. The difficulty is due to the previously discussed austenite transformation during the tension test and is completely removed if the *sharp-notch - yield strength ratio* rather than the notch - tensile strength ratio is used.

For the reasons discussed above the alloy comparisons in this paper were made on the basis of plots relating the sharp-notch - yield strength ratio to the yield strength to density ratio. Particular attention is given to the sharp-notch - yield strength ratio, σ_{NS}/σ_{ys}, at 650 F and −110 F, plotted against the 650 F yield strength to density ratio (σ_{ys}/ρ), which serves as a baseline indicator of alloy strength. This procedure recognizes the fact that the airplane will be designed primarily on the basis of elevated temperature properties but that structural safety must be considered at the lowest operating temperature. The room-temperature properties are of interest, but primarily for the purpose of formulating material specifications and in fabrication studies.

Various Conditions of AM 350:

The results of this approach are best illustrated by the data for AM 350 which cover a rather wide range of yield strength levels obtained by different combinations of cold reduction and tempering temperature. The σ_{NS}/σ_{ys} values at −110 F and at 650 F are plotted against σ_{ys}/ρ at 650 F, in Fig. 8. These plots have been derived from curves such as those shown in Figs. 2 and 3. The various symbols identify the tempering temperatures employed. Different cold reductions produced the different strength values plotted for each

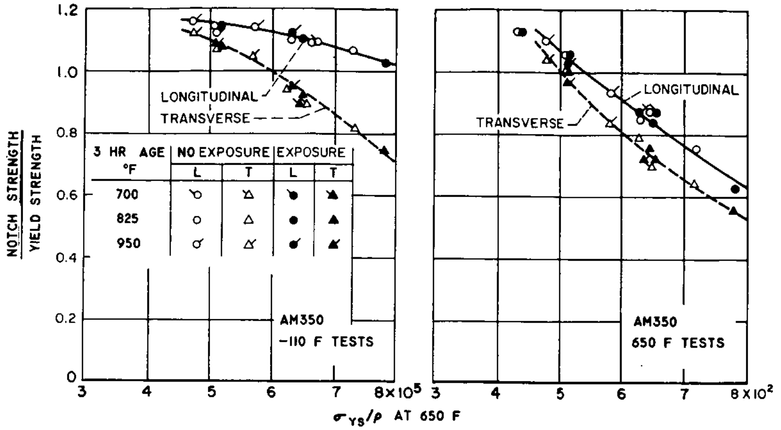

FIG. 8.—Sharp-Notch Yield Strength Ratio Before and After Exposure for Various Conditions of AM 350 as a Function of the 650-F Yield Strength to Density Ratio.

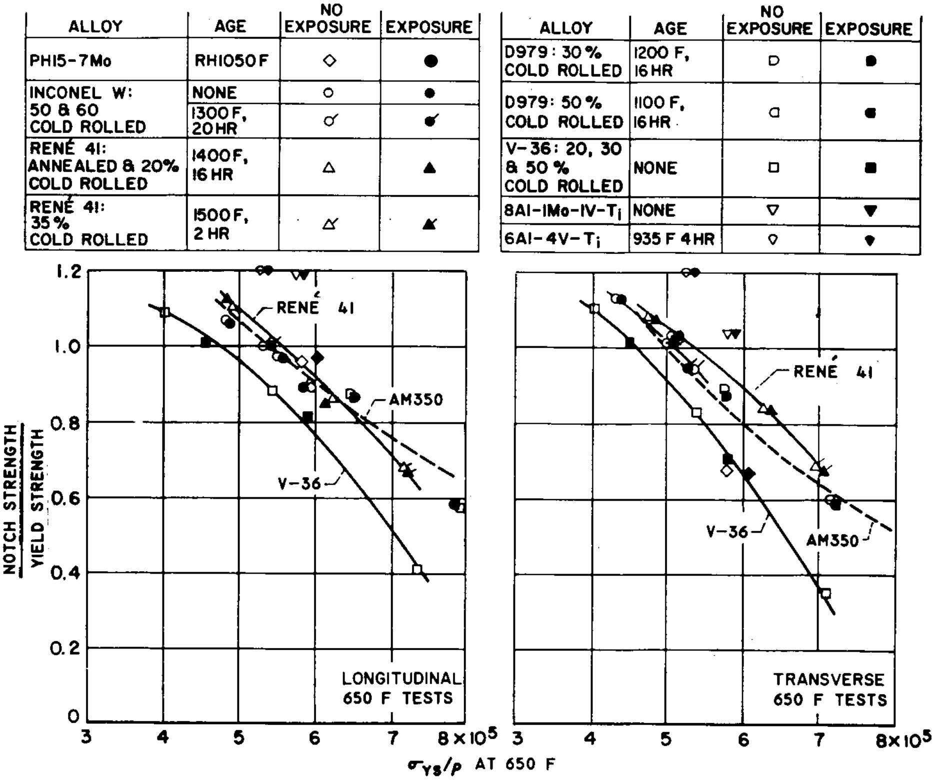

FIG. 9.—Comparison of Various Alloy Conditions at 650 F: Sharp Notch to Yield Strength Ratio at 650 F Versus Yield Strength to Density at 650 F.

tempering temperature. For all conditions investigated the longitudinal or transverse notch-strength ratios of this alloy are strongly dependent on the yield strength.

the cooperating organizations. It will be noted from Figs. 9 and 10 that where data are available for a given alloy at various strength levels, the notch - yield strength ratio decreases continuously

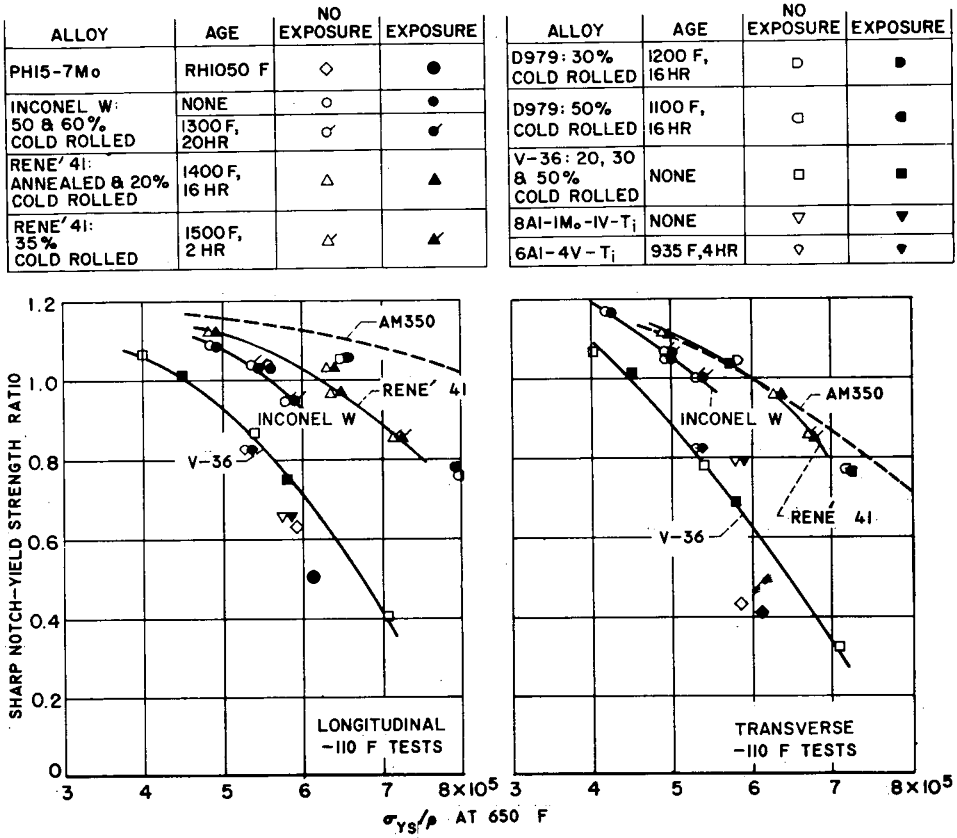

FIG. 10.—Comparison of Various Alloy Conditions at −110 F: Sharp Notch to Yield Strength Ratio at −110 F Versus Yield Strength to Density at 650 F.

Comparison of Various Alloys:

The longitudinal and transverse sharp-notch - yield strength ratios are shown in Fig. 9 as a function of the 650-F yield strength to density ratio for various alloys tested at 650 F. Similar plots are given in Fig. 10 for the −110-F data. These representations include all the alloys for which results were previously presented[7] as well as selected data from

with increasing yield strength to density ratio.

Considering first the 650-F data (Fig. 9), the titanium alloys exhibit the highest toughness at σ_{ys}/ρ values greater than about 500,000. On the other hand, V-36 exhibits the lowest notch - yield

[7] Data without exposure for V-36, 50 per cent cold rolled, have been added to these representations.

strength ratios over the entire range of strength levels investigated. The relative position of the remaining materials depends on the testing direction. In the longitudinal direction the two precipitation hardening steels and superalloys fall into a rather narrow band, while in the transverse direction the superalloys appear to possess superior toughness, particularly at the higher σ_{ys}/ρ values.

The −110-F data (Fig. 10) indicate that the titanium alloys, V-36 and PH15-7Mo, possess considerably lower toughness at −110 F than do AM 350 or the superalloys. Some loss in toughness of the titanium alloys at subzero temperatures is expected and is likely a function of their interstitial element content (7).

PRACTICAL IMPLICATIONS OF RESULTS

The program described has succeeded in producing useful information in several respects, namely: (1) available strength potential in the temperature range of interest as limited by fracture toughness; (2) the influence of test temperature on strength and toughness; (3) the influence of directionality on the toughness, and (4) exposure effects on toughness. The following section summarizes this information.

Available Strength Potential:

Yield strength to density ratios well above 700,000 at 650 F characterize the most heavily cold worked conditions of AM 350, V-36, and D979, and even higher values could be obtained by application of further cold rolling. However, the sharp-notch - yield strength ratios of these alloy conditions are 0.6 or less. Previous experience indicates that extreme care should be taken to avoid small cracks in structures built of materials having ratios this low. It is, of course, impossible at this time to set down any fixed acceptable minimum sharp-notch - yield strength ratio, or for that matter any corresponding value of fracture toughness. However, considering the very high reliability requirements and the possible influence of as yet undetermined factors which may reduce the toughness, the authors tentatively suggest that the most promising materials should have ratios of unity or above in both the longitudinal and transverse directions over the temperature range between −110 and 650 F. On this basis a 650-F yield strength to density ratio between 500,000 and 550,000 is a possible upper limit for the steels and superalloys shown in Fig. 9.

Table II lists the highest strength condition of several alloys having notch - yield strength ratios above unity at all test temperatures. Various properties are summarized in this table. The smooth strengths are averages of longitudinal and transverse data while the notch - yield strength ratios and elongations are the lowest values for the two testing directions. The properties of mill annealed Ti-8Al-1Mo-1V have also been added to Table II since it is quite strong and very tough at 650 F. However, as mentioned previously, this alloy has a transition temperature of about 250 F (see Fig. 7) and low toughness at subzero temperatures would be expected. The significance of this behavior is not yet clear since the alloy is quite new and it is known that special duplex annealing treatments can improve the room-temperature sharp-notch properties and presumably lower the transition temperature. The superalloy D979 is not listed in Table II because the lowest strength conditions investigated (corresponding to 30 per cent cold rolling) had a notch - yield strength ratio below unity at 650 F. However, it will be noted from Fig. 9 that the behavior of this alloy is quite similar to that of René 41 and it would be expected that lower

TABLE II.—SMOOTH AND SHARP-NOTCH PROPERTIES OF SEVERAL ALLOYS AT THREE TEST TEMPERATURES.[a]

Alloy	Condition	Properties at 650 F				Properties at Room Temperature				Properties at −110 F			
		σ_{YS}/ρ	Ultimate Tensile Strength, psi	σ_{NS}/σ_{YS}	Elongation in 1 in., per cent	0.2 per cent Yield Strength, psi	Ultimate Tensile Strength, psi	σ_{NS}/σ_{YS}	Elongation in 2 in., per cent	0.2 per cent Yield Strength, psi	Ultimate Tensile Strength, psi	σ_{NS}/σ_{YS}	Elongation in 1 in., per cent
AM350 CEVM	20 per cent cold rolled + 825 F, 3 hr	510 000	170 000	1.00T[b]	7.5	178 000	220 000	1.10T	24	200 000	270 000	1.05T	22
Inconel W	65 per cent cold rolled	530 000	170 000	1.00L[b]	4L	183 000	195 000	1.03L	2L	195 000	210 000	1.03L	3.5L
René 41	annealed + 1400 F, 16 hr	485 000	184 000	1.07	23	153 000	208 000	1.10	22	215 000	162 000	1.10	26
Ti-8Al-1Mo-1V	mill anneal 1450 F	580 000	115 000	1.03T	11	145 000	155 000	0.70L	18	160 000	165 000	0.64L	14

[a] Average of longitudinal and transverse values unless noted. No effect of exposure was noted for these alloy conditions.
[b] T = transverse; L = longitudinal.

amounts of cold working would yield a relatively strong metal condition with notch - yield strength ratios above unity at all test temperatures.

Influence of Test Temperature:

In the case of the precipitation hardening stainless steels and superalloys the smooth tensile and yield strength exhibit only a small temperature-dependence in the temperature range between 500 and 650 F. On the other hand, a relatively strong temperature-dependence of the smooth strengths is noted for the titanium alloys in this same temperature range.

With the exception of the titanium alloys, all materials investigated exhibited a lower notch - yield strength ratio at 650 F than at room temperature. The magnitude of this decrease appears to vary with the alloy and its condition with the superalloys D979 and René 41 showing the least effect. A decrease in the notch - yield strength ratio does indicate a loss in toughness. However, it is not possible to translate the changes in notch - yield strength ratio into corresponding changes in the actual fracture toughness. The cause or significance of this loss in toughness is not clear at the present time. It would seem reasonable to assume that it may be related to time- and temperature-dependent metallurgical instabilities. In the case of AM 350 this assumption appears quite reasonable since a definite loss in toughness also accompanies the exposure. In the case of the superalloys no exposure effects were observed; however the possibility exists that the exposure times were not sufficiently long. Quite obviously additional research is needed in this area to define the mechanisms responsible and to develop stabilization treatments.

Influence of Directionality:

It might be expected that heavily cold reduced sheet (not cross rolled) would exhibit lower toughness in the transverse direction. However, significant directionality of toughness was observed only for the AM 350 and V-36 alloys. For AM 350 lower transverse toughness might be expected due to the presence of free ferrite stringers. In this connection, it is interesting to note that the heat treated condition of PH15-7Mo exhibits a larger directionality than does AM 350. This might be expected since the former alloy contains more free ferrite than the latter. The directionality observed in the titanium alloy is characteristic only of this particular sheet and does not necessarily represent that to be expected in strip product.

Apparently the factors causing directionality of fracture properties are not yet well defined. However, it is known that low transverse toughness results from fibering associated with a second phase or, in the case of metastable steels, by transformation during the rolling (6,7).

Exposure Effects:

No creep could be detected during the exposure with the strain-measuring equipment employed (see Appendix II[8]). However, there is no question that long-time exposure at low stresses and at temperatures well below the aging temperature can produce an increase in yield strength and a significant decrease in sharp-notch strength for precipitation hardening stainless steels. In the case of AM 350 the deleterious effect of exposure increases with both cold reduction and aging (tempering) temperature. It is possible that this loss in toughness is due to a diffusion-controlled structural change and therefore may be a function

[8] Measurements were made of the notch root radii on selected specimens following the exposure. Within the limits of the optical comparator resolution (0.00025 in.) no change in the radii could be determined.

of time, temperature, and applied stress. Certain superalloys, such as Inconel W, René 41, and D979, are free of exposure effects under the conditions imposed in this investigation and are undoubtedly more stable than the precipitation hardening stainless steels. However, as mentioned previously, longer time or higher stress exposure of these alloys may reveal instabilities.

The significance of the exposure effects observed cannot be established without additional investigations. This problem is one of the most critical facing the designer and efforts should be made to develop methods for predicting the influence of very long exposure times from relatively short-time data.

Acknowledgments:

The authors wish to express appreciation to the various alloy producers who cooperated in furnishing the sheet. We wish to thank J. W. Freeman of the University of Michigan and Volker Weiss of the University of Syracuse for permission to include some of their data in this paper. In addition, we acknowledge the helpful suggestions of M. H. Jones of the Lewis Research Center, NASA, in formulating the program and developing the test techniques. We also acknowledge the assistance given by G. Succop and S. Barnosky, both of the Lewis Research Center, in performing the large number of required tests.

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APPENDIX I

ALLOYS UNDER INVESTIGATION

The various alloys under investigation are listed in Table III which gives the material conditions and the cooperating organizations along with the names of the principal investigators. All sheet is 0.025 in. thick with the exception of Ti-8Al-1Mo-1V, which is 0.020 in. thick. The titanium alloys, René 41, and Waspalloy, are hand rolled; the remainder of the materials were strip rolled. Various aging treatments were applied to the AM 350 and AM 355 alloys. Generally only one aged condition is being investigated for each cold rolled condition of those superalloys normally strengthened by aging.

TABLE III.—ALLOYS UNDER INVESTIGATION IN THE SCREENING PROGRAM.

Type	Alloy	Conditions	Organization[a]
Straight stainless steels	AISI 301	34, 50, and 60 per cent cold rolled	SURI
Precipitation hardening stainless steels	AM 350 and AM 355	20, 30, and 45 per cent cold rolled	NASA
	PH15-7 Mo	RH1050	SURI
Titanium alloys	6Al-4V	annealed and aged	SURI
	8Al-1Mo-1V	annealed	NASA
	5Al-2.75Cr-1.25Fe	aged	SURI
Superalloys	René 41	annealed, 20 and 35 per cent cold rolled	UM
	Inconel W	50, 65, and 80 per cent cold rolled	NASA
	A286	30, 50, 65, and 80 per cent cold rolled	UM
	N-155	40, 55, and 65 per cent cold rolled	UM
	L-605	25, 35, and 45 per cent cold rolled	UM
	V-36	20, 30, and 50 per cent cold rolled	NASA
	D979	30, 50, 65, and 80 per cent cold rolled	UM
	Waspalloy	annealed, 20 and 40 per cent cold rolled	

[a] SURI, Syracuse University Research Inst., Syracuse, N. Y.: Investigator, V. Weiss.
NASA, Lewis Research Center, Cleveland, Ohio: Investigators, authors.
UM, University of Michigan, Ann Arbor, Mich.: Investigators, J. Freeman and J. Rowe.

APPENDIX II

TESTING TECHNIQUES EMPLOYED BY THE AUTHORS

Specimens were exposed to temperature and stress by loading in conventional creep machines. By use of the pin blocks shown in Fig. 11 four specimens could be series-connected between the upper and lower loading yokes of a single machine. This series of specimens was heated by two 12-in. long resistance furnaces stacked one on top of the other. In order to assist in obtaining uniform temperature distribution a 24-in. long 6061-T6 aluminum tube (0.065-in. wall) was inserted into the furnaces. With appropriate shunting of the furnace windings, the temperature along the gage length of the four specimens did not vary by more than ±5 F. Temperature readings were taken by means of chromel alumel thermocouples. In the case of smooth specimens a thermocouple was tied at each end of the gage section and for notched specimens the thermocouples were spot welded approximately 0.25 in. from the notch plane.

Extension during exposure was measured by means of a dial indicator attached to the upper head of the creep machine. This dial could be read to 0.0001 in., corresponding to a strain in a 2-in. gage length of 0.005 per cent. As mentioned previously, no creep could be measured on any of the alloys using this technique.

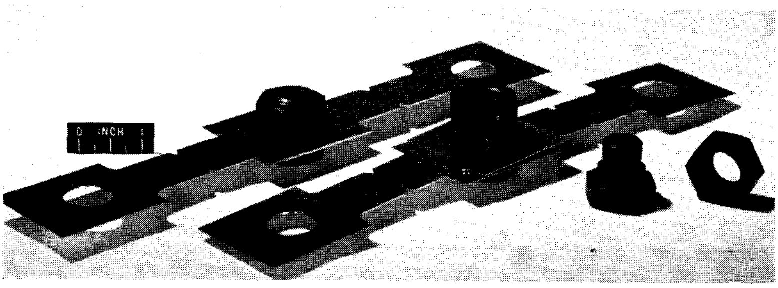

FIG. 11.—Pin Blocks with Specimens Showing Method of Series Connection.

Smooth tension tests were conducted using a differential transformer type strain gage connected to an autographic recorder. Load extension diagrams were obtained somewhat beyond the region of yielding. The approximate tensile loading rates were as follows: (1) at room temperature and −110 F, 4300 psi per sec for smooth specimens and 2300 psi net section stress per sec for notched specimens; (2) at 650 F, 2800 psi per sec for smooth specimens and 1500 psi net section stress per sec for notched specimens.

The specimens were immersed in a bath of dry ice and ethyl alcohol for tension tests at −110 F. Tension tests at elevated temperature were conducted using a conventional resistance furnace and the same thermocouple arrangement described above for the exposure.

DISCUSSION

MR. M. A. MELCON[1] (*presented in written form*).—The paper is an excellent presentation of the problems involved in the selection of materials for the Mach 3 supersonic transport and of the approach taken to screen the many candidate materials.

We are in agreement with the premise of the paper that fracture toughness and stability of mechanical properties under long-time load at temperature are two of the most important material characteristics for the application under consideration.

The authors have chosen to present their results on toughness as a ratio of the notch strength to the tensile yield strength of the material. Notwithstanding the reasons they give for doing this, it is felt that from the standpoint of the designer the notch to ultimate strength ratio is a more meaningful parameter. For the classes of materials under consideration the ratio of yield to ultimate strength is very high and hence tensile yield strength would not be a governing factor in design. This results from the fact that in aircraft design the usual factor of safety between limit loads at which yield would be a consideration and ultimate loads at which the structure shall not fail is 1.5.

Another point to consider when comparing notched-to-unnotched strength ratios is that a reduction of the ratio with a decrease in temperature is not necessarily detrimental provided the absolute value of the notch strength is not reduced. A case in point may be illustrated by the data shown for the AM350 material in Fig. 2 of the paper. For this material with 20 per cent cold reduction exposed to both stress and temperature, the notched-to-unnotched strength ratio is approximately 0.92 at room temperature and 0.77 at −110 F, while the absolute value of notch strength is about 204,000 psi at both temperatures. The decrease in the ratio is due to the increase in the tensile strength at −110 F, which generally would not be exploited in normal aircraft design.

Again with regard to notch strength, the authors suggest that suitable materials for the trisonic transport should have a notched-to-unnotched ratio of unity or better in both the longitudinal and transverse directions. It should be pointed out that highly successful and reliable aircraft structures have been constructed from materials which do not meet this criteria. For example, the notched-to-unnotched ratio (based on ultimate tensile strength) for 7075-T6 aluminum alloy in the transverse direction is 0.72. Even though it is highly desirable to use a material which is insensitive to cracks and notches, structural integrity can also be achieved by utilizing design features which will compensate for materials which have moderate crack sensitivity. This approach may be taken if the latter materials have other advantages which would result in an over-all design which is more efficient.

The authors state that the "elastic moduli are not presented in this report but are available to those who may need

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this information. The elongation is not reported since it is of primary concern in fabrication and does not relate to the alloy properties under study." It is felt that the value of the paper would have been enhanced if both of these properties had been reported. Elastic moduli are used directly in design to evaluate stiffness, and while elongation does not enter into many strength calculations directly, it is another parameter which is used to establish an order of merit for materials.

The authors state the following: "The room-temperature properties are of interest, but primarily for the purpose of formulating material specifications and in fabrication studies." It should be pointed out there will be many design conditions for the airplane which will involve room-temperature properties (after exposure) of the material. Examples of such conditions are landing, taxiing, low-level gust penetration, and so on. Hence these properties cannot be ignored in the design of the aircraft.

The authors are to be complimented on the extremely useful data and analysis which they have presented for without such information the design of the supersonic transport could not be carried forward.

MR. J. V. HACKWORTH[2] (*presented in written form*).—The authors are to be congratulated on their well-planned program for notch testing of alloy sheet. The data generated are a much needed addition to the study of fracture toughness and its measurement. This is a critical area where knowledge is limited, particularly in selection of the optimum test bar configuration, determination of parameters to be measured, and correlation with actual performance of structures.

The sharp notched tension specimen used by the authors is a convenient test for a qualitative measurement of fracture toughness. The writer has used it extensively for comparison of alloys and selection of optimum processing and heat treatment cycles. It is felt, however, that the use of the sharp-notch strength - yield strength ratio as a measurement of fracture toughness may be somewhat misleading in certain cases. For example, the sharp-notch strength of an alloy sometimes increases as the yield strength is increased, although at a different rate such that the notch to yield strength ratio decreases. This is the case for the authors' data on the influence of cold reduction upon AM350 and Inconel W as shown in Figs. 2 and 5.

The authors, in their discussion of Fig. 2, point out that the sharp-notch strength - yield strength ratio for AM 350 decreases as cold reduction is increased. At test temperatures of room temperature and −110 F, however, notch strength actually increases with per cent reduction and reaches a maximum at 30 per cent. The notch to yield ratio decreases because the yield strength increases at a disproportionately faster rate than the notch strength. This raises a question as to whether the notch strength to yield strength ratio or the notch strength itself should be at a maximum to insure the highest fracture toughness at a given design stress level. For example, at a design stress of 175,000 psi (the yield strength obtained with 20 per cent reduction) a more reliable structure might be obtained by using a 30 per cent cold reduction. The part would be stressed to a lower percentage of its yield strength, but sensitivity to notches would be decreased with no increase in weight.

MR. E. A. DOLEGA[3] (*presented in written form*).—The authors' approach to the

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screening program is appropriate in that they are considering (1) unstable crack propagation resistance and (2) stability of mechanical properties. However, they contradict themselves in the explanation of the use of the sharp-notch yield strength ratio as the basis for the selection of materials. They state that by using the above ratio rather than the notch tensile strength, the effect of austenite transformation during tension testing of 20 per cent cold reduced AM350 is completely removed. This is using numbers to nullify a test result which gives them a material property that they are seeking, namely, stability of mechanical properties. This phenomenon has been encountered in the use of cold-worked AISI 300 grade stainless steels at cryogenic temperatures and is considered important.

A second point is the rate of loading during the tension test. The authors do not explain why the rate varied between the smooth and notched specimens. We would like to know if the authors had conducted any tests to determine whether this difference in the rate of loading caused a variation in properties.

MR. PAUL KUHN[4] (*presented in written form*).—The NASA screening program for supersonic transport skin materials, on which Messrs. Espey, Bubsey, and Brown have given a preliminary report, presents data of inestimable value to designers.

This paper furnishes the basis for many discussions on choice of materials for supersonic transports. In view of this, it may be well to offer some comments either to bring out a somewhat different point of view on interpretation or to reflect a point of view more closely associated with design than with materials properties.

The authors comment that the ASTM 1-in. edge-notch specimen "would possibly lack useful sensitivity at yield strength to density values below about 550,000." It would be well to add that this specimen is also questionable for very high-strength materials. The third report of the special ASTM Committee on Fracture Testing of High-Strength Sheet Materials indicates that H-11 should have a root radius of about 0.00025 in. in order to simulate cracks. Machining such a radius within acceptable tolerances is hardly practical. The radius of the specimen is specified by the authors as "0.0007 in. max." The limits of resolution of the optical comparator used are stated as 0.00025 in. Thus, the accuracy of checking would be very poor even if the notches were formed perfectly, which is very unlikely. This writer suggests, therefore, that the radiused notch be abandoned in favor of fatigue cracks in future work (except for special research).

The authors do not report all elongation values because "elongation does not relate to the alloy properties under study." In a recent paper[5] it has been shown that the notch strength—one of the two properties under study—can be calculated fairly well from the elongation and two general curves of size-effect constants for aluminum alloys. Preliminary attempts to apply this method (identical except for derivation of the size-effect constants) to titanium alloys show considerable promise. In order to facilitate further study of this method, it is suggested that elongations be measured and reported as heretofore.

The authors discuss notch toughness using the ratio of notch strength to yield strength. Aware of the fact that aeronautical engineers prefer to deal with the

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[5] P. Kuhn and I. E. Figge, "Unified Notch Strength Analysis for Wrought Aluminum Alloys," NASA TN D-1259, May, 1962.

notch strength to ultimate tensile strength ratio, they justify their choice by pointing out that the customary notch - ultimate tensile strength ratio gives (in one case) a misleading picture of toughness variation. It appears self-evident to this writer that any ratio of two quantities may be misleading, in some cases, if one is interested in only one of the quantities (notch strength). Thus, the convenience of dealing with a single number (ratio) instead of two numbers must be weighed against the danger of being misled. In this writer's opinion, a ratio is useful for preliminary choice of materials, the ratio of notch strength to ultimate tensile strength being more useful to aeronautical engineers because it ties in better with the basic design procedure for aircraft structure. As the final design of the structure is approached, however, ratios become useless; it becomes necessary to deal directly with the notch strength itself.

Finally, it may be well to mention that the statement "the airplane will be designed primarily on the basis of elevated temperature properties" is debatable. There has not been enough experience to generalize safely, but the present indications are that the critical design conditions are likely to occur at room temperature, and that the elevated temperature will make itself felt chiefly through deterioration of room-temperature strength due to long exposure.

With regard to test technique, would the authors explain why they used constant loading rate rather than constant strain rate, as recommended by the ASTM?

MESSRS. C. W. ALESCH AND F. F. W. KROHN[6] (*presented in written form*).—The suggestion in this paper to the effect that the most promising materials should have notch - yield strength ratios of unity or above in both the longitudinal and transverse directions may, if taken as a working limit, lead to the exclusion of many potentially useful airframe structural materials from consideration.

It is of importance to note that notch-strength ratio and fracture toughness are of importance in structures which operate in tension, such as pressure vessels, tanks, and fuselage bodies. Very often, and especially so in fuselages, design considerations aside from tension, such as fatigue, tend to be of critical importance and serve to limit the stress at which the structure is expected to operate throughout the major portion of its life. In this regard, it can be mentioned that pressurized aluminum alloy fuselages designed at stress levels in the order of 10,000 psi are not uncommon. In these cases, because of the fatigue consideration, the design stresses are far below the engineering strengths of the material employed. It can also be indicated that notch-strength ratio data for a widely used fuselage material, 7075 alloy, are available to show that the notch-strength ratio of this material, for example, is marginal on the basis of a unity notch ratio criterion. Nonetheless many 7075 aluminum alloy fuselage structures can be pointed out after 10 to 15 years of continuing and successful service to verify the soundness of material selection exercised in their design.

The point to be taken from this is that the design conditions at hand in given cases govern material selections for production articles. It can be pointed out, for example, that the Ti-8Al-1Mo-1V alloy mentioned in the paper has a notch strength at room temperature of slightly more than 100,000 psi and a sharp notch - yield strength ratio of about 0.65. In view of the 25,000 psi stress representing working conditions, the poorest notch strength is four times the assumed working stress, and thus proposals which con-

[6] Design Specialist—Materials and Design, General Dynamics/Convair, San Diego, Calif.

sider the use of materials such as this in designs can be considered reasonable because of the very remote possibility of a working stress even exceeding the notch strength figure. In fact, in transport design the ultimate design stress is 3.75 times the working stress and the limit stress which is not to be exceeded in operation is designed to 2.5 times the working stress. The proof of these things, of course, is in careful design analysis of structures which are in hand.

MR. R. T. AULT[7] (*presented in written form*).—The authors are to be congratulated on their method of approach and thoroughness in attempting to utilize simplified test techniques to screen a large number of sheet alloys for potential use as a skin material for a commercial trisonic transport.

It is perhaps quite arbitrary whether a notch - yield strength ratio or a notch - tensile strength ratio is used as a qualitative index. The authors have chosen to use a notch - yield strength ratio as it eliminates the problems encountered in the AM350 alloy which undergoes an austenite to martensite transformation during the tension test, which raises the tensile strength but not the yield strength. There is, however, some information which can be gained from the notch-strength ratio (NSR) which cannot be obtained from the notch-yield ratio (NYR). Included in the tensile strength of a material, but not the yield strength, is the material's work hardening capability; that is, the difference between the tensile strength and yield strength is a measure of the work hardening capacity of the material, therefore, the NSR provides a measure of the material's ability to work harden in the presence of a notch, which cannot be obtained from the NYR. Thus, a material's NYR can be greater than unity and the NSR less than unity. This is illustrated in Figs. 5 and 6 for the Inconel W and V-36 alloys. It should also be mentioned that as the yield stress of a material can be quite sensitive to strain rate while the tensile strength is rather insensitive to strain rate, caution should be exercised to insure that different investigators conduct their tension tests at the same strain rate, especially when only one tension test is being used to establish the yield stress. In agreement with the authors it is felt that the NYR can be useful as a minimum fracture toughness quality index, and that no material should be given serious consideration for further study if it has a notch - yield strength ratio less than unity. Thus useful, but different types of screening information can be obtained from both the NSR and NYR.

The authors have pointed out that there is a loss in toughness, or a significant lowering of the notch - yield strength ratio at 650 F, especially in the AM350 alloy, which is not understood at the present time. This is an extremely important observation as strain aging in high-strength steels, and associated delayed failure, are known to occur at supertransition temperatures within the range of design interests for potential trisonic transport materials. An Air Force program (Contract No. AF 33(637)-7512) has recently been initiated in order to study strain aging and delayed failure in high-strength steels. To date we have found a strain-rate-dependent embrittlement, and associated delayed failure, to occur in the 400 to 650 F temperature range in 300M, 4340, and nickel-cobalt-molybdenum maraging steels. The strain rate dependent embrittlement is found by a significant drop in the notch tensile strength in the embrittlement region. The mechanism responsible for this behavior is not understood as yet; it may be a stress-induced diffusion of an inter-

[7] Metals and Ceramics Laboratory, Materials Central, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

stitial or it may involve stress-induced solution and reprecipitation of carbides. But regardless of the responsible mechanism, it is strongly recommended here that any alloy which has an indication of this type of embrittlement and is being considered for further follow-up studies after the screening program should also be thoroughly investigated for susceptibility to strain aging and delayed failure type of embrittlement.

A comment with respect to Table II, and elsewhere, is that notch strength of materials is commonly expressed as a ratio with ultimate tensile strength.

MESSRS. A. J. HATCH,[9] D. L. DAY,[10] AND E. F. ERBIN[11] (*presented in written form*).—The authors have studied the influence of sharp notches and temperature on the load-carrying ability of the Ti-8Al-1Mo-1V sheet alloy in the 1450 F, 8 hr, furnace-cooled condition, and have

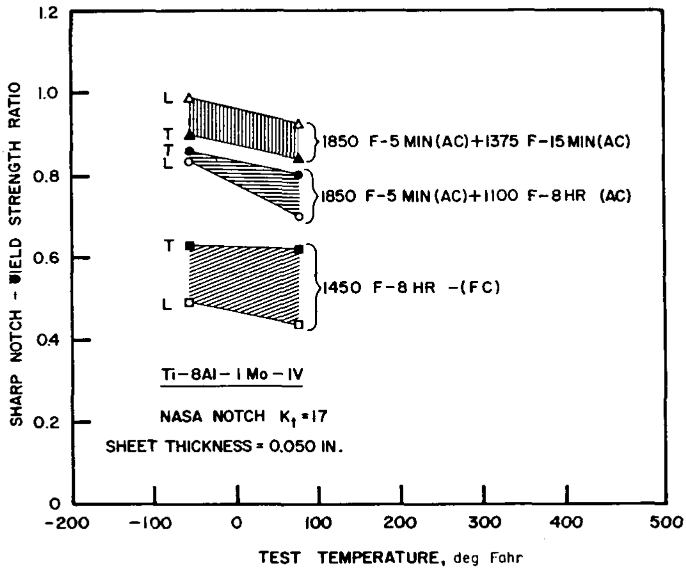

FIG. 12.—Sharp-Notch Yield Strength Ratio at Two Test Temperatures for Single and Duplex Annealed Ti-8Al-1Mo-1V.

MR. D. C. LAUVER[8] (*presented in written form*).—A more important reason for precluding loss of pressurization at operating altitude than "the longer times necessary for descent to a safe altitude" is the inability of humans to survive at altitudes much in excess of 45,000 ft outside of a pressurized atmosphere. It is believed this fact is worthy of emphasis to show the strong need for materials data on fracture toughness.

presented the data in two forms in their Fig. 7. The absolute values of notch strength encountered by the authors show mixed behavior to lower temperatures. The longitudinal values show some decrease while transverse values gain slightly as temperature drops. The spread between longitudinal and transverse is

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[9] Senior Research Metallurgist, Titanium Metals Corp. of America, Henderson Technical Laboratories, Henderson, Nev.

[10] Titanium Metals Corp. of America, New York, N. Y.

[11] Assistant Manager, Technical Service and Development, Titanium Metals Corp. of America, New York, N. Y.

relatively small and the average of the two shows essentially no difference between 650 F and −110 F. However, the uniaxial strength, both yield and ultimate, are increasing as temperature drops. Thus, the ratio of notch strength to yield strength decreases as temperature drops. The question is raised as to the correct interpretation of the significance of this behavior. If the absolute value of notch strength is retained at a constant value, what is the significance of a decreasing notch to uniaxial strength ratio?

The authors have observed from Fig. 7 that, due to the notched-unnotched ratio drop, low toughness at subzero temperature might be expected. They note that this behavior for the 1450 F, 8 hr, furnace-cooled condition might be improved upon by duplex annealing treatments.

The alloy's sharp-notch behavior has now been investigated in several duplex annealed conditions. The results of one study performed by Titanium Metals Corp. of America are shown in the accompanying Fig. 12. The authors' statement of improved notch properties as a result of duplex annealing have been confirmed previously using an 1850 F air cooled + 1100 F for 8 hr, air cooled duplex anneal. The most recent study also includes the use of a higher stabilizing temperature of 1375 F. It is noted that an 1850 F air cooled + 1375 F for 15 min, air cooled treatment results in a further improvement in sharp-notch - yield strength ratio. The uniaxial strength properties for these duplex annealed conditions show no noticeable change from the 1450 F, 8 hr, furnace cooled condition.

There now is substantial evidence that the fracture toughness of the Ti-8Al-1Mo-1V sheet alloy is markedly improved by the use of duplex annealing treatments.

MR. E. J. RIPLING.[12]—The authors of this paper have made a substantial contribution to our understanding of notch behaviors by publishing a long series of reports on the subject. In these previous studies, notch strength ratio had been defined as sharp-notch strength divided by the unnotched tensile strength. In the present paper, however, the ratio of sharp-notch strength to unnotched yield strength is used to describe relative toughness. This new toughness criterion was selected by the authors because it seemed more rationally to explain the behavior of a number of the surveyed materials as discussed in the "Comparison of Alloys" section of their paper. Additional reasons, based on more general considerations, are given for using yield strength in the ratio in the "Screening Tests" chapter of the authors' reference (8).

Although it is recommended that the ratio between the notch strength and the tensile strength be reported in screening studies, this reference also states that the ratio of notch strength to yield strength may be used. Two advantages of the latter are cited. One is particularly important to this paper; namely, materials with a notch to yield strength ratio of unity or more have a K_c high enough to arrest a crack of twice the plate thickness; materials whose ratio is less than unity cannot arrest such a crack. Even though this ratio may be high, since cracks larger than twice the plate thickness may be tolerable in skin materials, it seems a more reasonable measure of relative toughness than notch strength-tensile strength ratios, since the latter has no contact with fracture toughness.

Not only does a notch strength - yield strength ratio of unity give the K_c for separating arrest and growth of a crack of a particular size, but it is also related

[12] Materials Research Laboratory Inc., Richton Park, Ill.

to the fracture appearance. For heat treated steels, at least, a completely shear fracture is found so long as the ratio of notched strength to yield strength is greater than one. Although complete shear fractures *always* occur when this ratio is above unity, 100 per cent shear also may be found for notch strength ratios lower than this. Again the use of notch strength to yield strength ratio is class. Notch strength ratio historically was introduced for comparing high-strength heat treated steels. Within this single class of materials, the shape of the stress-strain curves (notched or unnotched) are similar. Hence, a correlation of notch strength ratio and service performance probably would have been equally successful if yield or tensile strength were used. This successful cor-

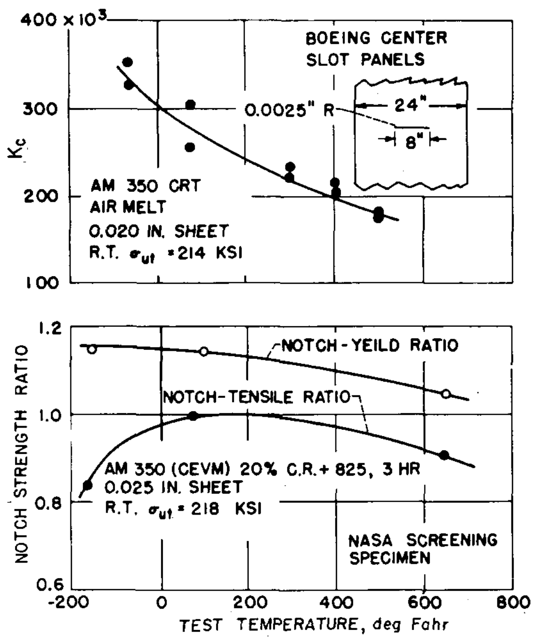

FIG. 13.—Comparison of Notch-Yield and Notch-Tensile Strength Ratios with K_c Values for Longitudinal Tests on AM350 CRT.

not ideal, but it does have advantages that are not found when the tensile strength is used in the ratio.

In spite of these apparent advantages of the relative toughness criterion that the authors have selected, most experience correlating service behavior with laboratory tests is based on a ratio involving tensile strength. Success with this correlation, however, appears to result from the fact that it has been restricted to materials of a particular relation might not have been found if it were carried out between classes of materials—for example, heat treated low-alloy steels and heavily worked stainless steels. In this screening study a variety of types of materials were tested, ranging from heavily worked stainless steels and superalloys to annealed titanium. The shape of the unnotched stress-strain curves were widely different so that the possibility of finding a correlation between notch strength ratios and service performance is probably enhanced by using yield strength.

MESSRS. G. B. ESPEY, R. T. BUBSEY, AND W. F. BROWN, JR. (*authors' closure*).—The authors wish to thank the discussers for their comments and additional information.

A considerable amount of discussion has been directed to the authors' use of the notch strength to *yield* strength ratio in analysis of the data. The airplane designer bases his working stresses on the ultimate tensile strength and consequently is in the habit of using the notch *tensile* strength ratio. We have no reason to dispute this design philosophy. However, we are not presenting design data but rather information for use in determining a materials' relative resistance to unstable crack propagation. The notch-tensile ratio may be used as an indicator of fracture toughness for many alloys but, as discussed in the paper, is not suitable when alloys transform during the tension test (for example, AM350 CRT).

Further arguments may be made to support the use of the notch-yield ratio rather than the notch-tensile ratio. These arguments are based both on actual material behavior and on fracture mechanics analysis. Regarding actual material behavior, the results for AM350 CRT in this investigation may be compared with fracture toughness data obtained by Boeing Airplane Co. for this alloy at nearly the same thickness. The longitudinal screening test data for AM350 (20 per cent cold rolled and 825 F, 3-hr age) has been plotted as a function of test temperature in the accompanying Fig. 13 using both the notch-tensile and the notch-yield strength ratio. Added to this representation are longitudinal fracture toughness values obtained on AM350 CRT by the Boeing Airplane Co. using 24-in. wide center slotted panels.[13] It is observed that the fracture toughness as determined by Boeing is higher at −60 F than at 500 F, and increases continuously with decreasing test temperature between these.

In contrast, the notch tensile strength ratio obtained from the authors' small specimens exhibits a maximum at room temperature and decreases with decreasing temperature. On the other hand, the notch-yield ratio indicates higher toughness at −60 F than at 650 F, in agreement with the wide panel data. Of course, the relatively small specimen employed by the authors is entirely inadequate to reveal the increase in toughness between room temperature and −60 F, since considerable plastic flow has preceded fracture on the net section. Under these circumstances the notch-yield ratio remains at a nearly constant value even though the toughness increases.

Another argument for the use of the yield rather than the tensile strength in the notch strength ratio can be made on the basis that the yield-strength ratio puts the results in closer touch with accepted methods of fracture mechanics analysis (8). Thus, the crack size $2a$ in an infinite plate which will be stable on a single loading to the yield strength σ_{ys} is given by the following:

$$2a = \frac{2K_c^2}{\pi\sigma_{ys}^2}$$

The fracture toughness K_c is a function of notch strength and therefore the notch-yield ratio becomes an indicator of the $2a$ value. Further arguments for the use of the notch-yield ratio on this basis are given by Mr. Ripling in his discussion. We agree with Mr. Kuhn

[13] It will be noted that the AM350 CRT tested by Boeing has a somewhat lower room-temperature tensile strength and was not vacuum melted. However, these differences should not influence the general behaviors observed as the test temperature is varied.

that no simple ratio can be of direct use in final design of the airframe. However, as Mr. Kuhn states, the ratio is useful for a preliminary choice of materials and that is the only use we have made of it.

Several discussers suggest that attention should be directed to the absolute value of the notch strength and its variation with temperature rather than to the ratio between notch strength and smooth strength. It should be emphasized that the notch strength alone is not necessarily an indicator of fracture toughness. An extreme example would be a comparison of H-11 steel tempered at 1000 F with the aluminum alloy 6061-T6. The NASA specimen room-temperature notch strengths are 80,000 psi for the steel and 45,000 psi for the aluminum alloy. The steel shows a completely flat fracture and a notch yield strength ratio of about 0.35 while the aluminum shows 100 per cent shear fracture and a notch yield ratio of about 1.15. The aluminum alloy is much tougher than the steel in spite of its lower notch strength. Unless materials are exceptionally brittle, fracture toughness cannot be determined solely from the notch strength. For most engineering alloys the crack tip plastic zone contributes to the fracture toughness, and as shown by Irwin (8), the radius of this zone is a function of both toughness and yield strength. The need for introducing the yield strength was also demonstrated in the above discussion on the use of the notch-yield strength ratio.

Mr. Dolega suggests that by using the notch-yield strength ratio we are ignoring the instability of AM350 CRT revealed by the smooth tension test. This type of structural instability is well known and was not of direct concern in this investigation. However, as discussed above, it can produce a misleading indication of fracture toughness when the notch-tensile strength ratio is employed.

Mr. Alesch and Mr. Melcon believe that materials with sharp-notch yield strength ratios below unity might be used in the supersonic transport because the normal working stresses are low and because design features can in part compensate for reduced toughness. There was no attempt on the authors' part to set an absolute limit on the notch-yield ratio for design purposes. However, it is quite evident that at a given yield strength to density ratio there is considerable variation between the toughness of the various alloy conditions investigated and it seems logical to concentrate future efforts on the toughest alloys unless it can be shown they are unsatisfactory in other respects. Furthermore, as emphasized by Mr. Lauver, it appears that greater attention must be given to crack propagation resistance in design of the supersonic transport than when designing conventional aircraft The new data on the Ti-8Al-1Mo-1V alloy presented by Messrs. Hatch, Erbin, and Day show a considerably improved toughness at room and low temperature, and this alloy is now on a par with the others given in Table II of the paper. This is an illustration of what can be accomplished by setting conservative requirements for toughness. This may invite re-examination of the heat treatment or composition of a given alloy system. The result can be a considerably improved product which permits greater reliability in the aircraft structure.

Mr. Kuhn suggests that the machined notch be abandoned and fatigue crack specimens substituted. It should be noted that the ASTM Committee on Fracture Testing of High-Strength Materials and the Aerospace Industries Assn. recommend the sharp-edge-notch specimen for screening purposes. It is true that fatigue cracks will yield somewhat lower strength value for *extremely* brittle alloys such as fully hardened H-11 (9). However, the sharp-notch test does not fail to reveal this temper of H-11 to be extremely brittle in comparison with conditions produced at higher tempering temperatures. For the great majority of materials having engineering interest, the 0.0007-in. maximum notch radius will adequately approximate a fatigue crack in the screening specimen. In this connection we refer to some results recently obtained by Weiss and Sessler (5) using the NASA sharply notched specimen and the same size specimen with edge fatigue cracks. These results are shown in Fig. 14 for 6Al-4V aged and PH-15-7Mo (RH 1050). There is no significant difference in the notch tensile strength ratios obtained using either specimen, even though the alloys were rather brittle at the lowest test temperature. We do not propose, however, that machined notches be substituted for fatigue cracks when actual fracture toughness is being measured.

Mr. Ault and Mr. Dolega call attention to possible strain rate effects. We have no knowledge of such effects on either the notch or smooth properties of the alloys studied but suspect they may be important in materials not stable during the tension test. We do not believe that the rather small variation in stress rates between smooth and notched specimens in this investigation would influence the results. In answer to Mr. Dolega, these rates were different because in all tests the same oil flow was supplied to the loading piston of the hydraulic tension machine. Consequently, the smooth specimens having the smaller area were subjected to a higher stress rate. We certainly agree with Mr. Ault that follow-up studies should consider susceptibility to strain age embrittlement.

Mr. Kuhn suggests that conventional elongations be reported since they may

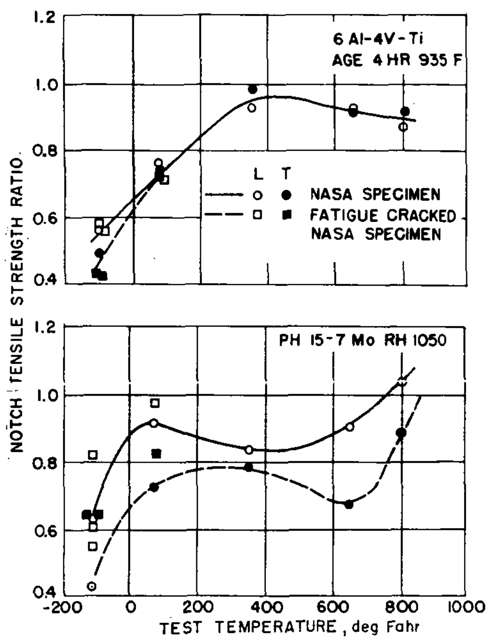

FIG. 14.—Notch Tensile Strength Ratio as Function of Test Temperature for Sharp Machined Edge Notch and Fatigue Edge Crack Specimens.

be used in calculation of the notch strength by means of a procedure outlined in his reference. This procedure involves a modified elastic stress concentration approach to the size effect in notched specimens combined with a correction for plasticity. The correction for plasticity involves the secant modulus corresponding to the ultimate tensile strength. This modulus may be calculated from the *uniform* elongation and tensile ultimate strength. It is suggested by Mr. Kuhn that the secant modulus may be estimated satisfactorily using the conventional elongation, which includes nonuniform strain, the amount depending on the alloy. Any method which bases a plasticity correction on elongation may encounter difficulty when attempting to account for the high notch strengths frequently observed in heavily cold-worked materials which necessarily have very low elongations. An example would be the Inconel W 65 per cent cold rolled (see Table II). Messrs. Kuhn and Figge (5) admit a measure for ductility associated with fracture might better be derived from the tensile reduction in area. However, it is not clear how such value could be used in his proposed plasticity correction.

Messrs. Kuhn and Melcon point out that the room-temperature properties may strongly influence the design. Under these circumstances, the screening test data do not lose their value but only require different representation.

Mr. Melcon properly states the importance of elongation and elastic properties to the designer. However, as previously stated, the present paper does not attempt to present design information and therefore these properties were excluded for the sake of brevity. It is planned to make all of the screening data available in detailed form in an NASA report and those wishing information not contained in this paper may consult the NASA document.

In conclusion, we realize that various opinions concerning design philosophy and lack of knowledge concerning the airplane configuration greatly complicate the materials picture. At this early stage, it is necessary to make many compromises and assumptions in the evaluation of alloys. Our hope is that the data presented have sufficiently general application that their usefulness will not be unduly limited by future design developments.